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Assessing the low-carbon effects of inter-regional energy delivery in China's electricity sector

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ABSTRACT

In China, the electricity sector consumes approximately 50% of the coal and emits 40% of the CO_2 from fossil fuel combustion. The unbalanced spatial distribution between energy resources and demands and the remarkable differences in power-generation capabilities among regions are important factors that impede decarbonization of China's electricity sector. Utilization of the abundant low-carbon energy resources in the central and western regions is restricted by limited local demand. Energy demand in these regions accounts for approximately 26% of the entire nation's demand. By comparison, the regions have more than 45% of the energy resources. However, long-distance energy delivery incurs considerable losses. At present, approximately 80% of inter-regional energy delivery uses primary coal transport and 20% travels by secondary electricity transmission. The Chinese government is planning to build an ambitious inter-regional transmission grid for energy delivery. We demonstrate that this plan would significantly change the current delivery patterns and improve delivery efficiency. Approximately 40% of inter-regional energy delivery would travel by secondary electricity transmission and a 25% improvement in the delivery efficiency of the entire system is expected. Therefore, utilization of low-carbon energy resources would be promoted and overall carbon emission would be reduced. Using a fine-grained electricity dispatch model to simulate and optimize the operation of the power system, the carbon emission mitigation potential is quantitatively assessed based on real planning data. The results indicate a significant 10% reduction in CO_2 emissions in 2030, amounting to 0.49 Gt. This reduction should be included as an important component for the sector's low-carbon budget. Finally, we assess the potential for further reductions in carbon emissions by making modifications to the planned transmission grid.

Contents

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1. Introduction

China is one of the major contributors to the recent emission surge, and the electricity sector is the largest single source of carbon emissions, consuming approximately 50% of China's coal and emitting more than 40% of China's CO_2 from fossil fuel combustion [1,2]. Considering the rapid increase in electricity demand, the scale of overall CO_2 emissions from the electricity sector would still experience a rapid increase in the future despite the installation of large-scale generation capacity based on renewable resources [3–5] and remarkable improvements in technology efficiency [6–9]. Several studies have estimated that the scale of annual incremental emission between 2010 and 2030 would be approximately 1.5–2.0 Gt [3,8,10]. This emission is roughly equivalent to Russia's annual CO_2 emissions in 2010 (the world's fourth largest emitter) [11]. Therefore, the electricity sector would be confronted with great challenges in the low-carbon era.

An important factor impeding the decarbonization of China's electricity sector is the unbalanced spatial distribution between energy resources and demands [12]. For example, the exploitable energy resources in the east region account for only 3% of the resources for the entire country, whereas the proportion of energy demand is up to 25% of the national demand. By contrast, the northwest region and Tibet account for approximately 22% of the total energy resources and only 8% of the total energy demand. Approximately 80% of coal reserves are located in the north and northwest regions [1]. Therefore, at present, long-distance energy delivery in the form of coal transport is necessary to support the energy demands in the east, south, and northeast regions. In 2010, inter-regional transport carried approximately 25% of the national coal consumption for power generation [1,3,13]. This situation incurs considerable energy losses and associated carbon emissions, which are estimated to be 0.17 Gt of CO_2, or 5% of the sector total in China [1].

Fig. 1. Division of regional power grids in China.

Another important factor impeding the decarbonization of the sector is the remarkable differences in the power-generation capacity (PGC) mix of the regions [14]. In 2010, non-fossil fuel power capacities, including hydro, nuclear, wind, solar, and other renewable power sources, accounted for 26.8% of the national PGC mix [1]; however, the regional distributions were extremely uneven. The central and south regions shared the highest proportions (45.3% and 43.1%, respectively), whereas the proportion of the north region was as low as 7.3%. Although the national low-carbon proportion of PGC will continuously increase in the future, this uneven regional distribution will be maintained or possibly even exacerbated [3–5]. The highest and lowest regional proportions would be 60.0% and 8.3% in 2020 and 56.4% and 11.3% in 2030, respectively. As a result, the generation carbon emission intensities (GCEI) of the regions also differ considerably. In 2010, the national GCEI was 695.2 g/kWh. The highest and lowest intensities were 827.7 g/kWh (the northeast region) and 567.4 g/kWh (the central region), a 40% difference. This gap is expected to widen in the future.

Electricity transmission is an efficient means of energy delivery, particularly over long distances [15], and a transmission grid is the only feasible carrier for the delivery of large-scale, low-carbon energy, such as hydro, wind, and solar power [12]. However, in present-day China, we find only small-scale transmission capacities between regions. In 2010, the inter-regional transmission capacity was only 40.2 GW, which was 4.2% of the national PGC [16]. The scale of energy delivered by transmission was relatively small—only 1/4 of that delivered by coal transport for power generation. To support the need for future large-scale energy delivery, increased delivery efficiency, and lower carbon emissions, the Chinese government is planning to build an ambitious inter-regional transmission grid (including cross-border connections) using ultra-high voltage (an alternating current of 1000 KV and a direct current ± 800 KV) transmission technology as a major component. In 2020, there will be an inter-regional transmission capacity of 258 GW (30 GW cross-border connections), accounting for 15% of the national PGC; this value is expected to increase to 370 GW in 2030 (60 GW cross-border connections). This inter-regional transmission grid will significantly change the current electricity supply and demand situation, which is primarily "regional self-balancing", and will reduce emissions.

1. First, electricity could be transmitted from low-GCEI regions to high-GCEI regions and thus cut overall carbon emissions.
2. Second, overall delivery efficiency might be enhanced by coordinating energy delivery in the form of coal transport and electricity transmission.
3. Third, the abundant low-carbon energy resources in the central and west regions could be utilized more effectively.

Decarbonization of the electricity sector has become a popular research topic in recent years. However, most of the studies are focused on analyzing the low-carbon effects from the generation side instead of on the transmission side [17–22]. Wang et al. present an assessment of low-carbon power-generation reserves in China and conclude that China has ample low-carbon energy resources to revolutionize its power structure [17]. Kannan et al. use the UK MARKAL energy systems model to analyze long-term uncertainties in low-carbon electricity-generation options [18]. Zhang et al. study the dynamics of carbon emissions baselines of electricity generation in India and China [19]. Some studies [23–26] consider low-carbon effects from the transmission side; however, such studies tend to have a narrow focus on a particular type of technology and fail to analyze the entire power system. Moreno et al. investigate the upgrades necessary to improve the efficiency of transmission system operation and the capacity required to support a low-carbon power system [23]. Wang et al. propose a conceptual smart grid that is friendly to the low-carbon generator and customers [25]. Mills et al. estimate the incremental transmission costs associated with wind development [26]. Several researchers have attempted to model and evaluate the emission reduction potentials of the sector and formulate low-carbon evolution roadmaps [8,27–35]. Zhang et al. model and evaluate the impacts of carbon mitigation-related measures on China's power sector, including carbon cap and trade and the application of carbon capture and storage [27]. Zhou et al. identify the main low-carbon factors in power systems to evaluate the low-carbon benefits from different sectors [29]. Zheng et al. evaluate and predict the carbon efficiency of electricity in the UK over the next decade [30]. Atkins et al. present a carbon pinch analysis of the New Zealand electricity industry [31]. Pękala et al. describe a modeling approach for energy system planning with carbon footprint constraints and assess the effect of some important technologies for carbon emission abatement [32]. Unsihuay-Vila et al. develop a model for the planning of integrated generation and transmission corridors incorporating sustainable energy development [33]. However, these studies do not consider the impacts of energy delivery, nor do they adequately integrate the operational characteristics of power systems. Therefore, a complete view of the contributions of energy delivery links to a low carbon target remains unavailable, and thus, we could not make the corresponding quantitative assessments.

To this end, we used a fine-grained electricity dispatch model to simulate and optimize the operation of power systems. Because this study aims to assess the maximum potential of CO_2 mitigation effects, the objective of the model is to minimize the overall carbon emissions of the sector, including emissions from not only fossil fuel combustion but also fuel exploitation and transport. The model also integrates formulations of the technical characteristics of power system operation for more accurate simulation. To a large extent, this model reflects an important policy on electricity dispatch in China, which is oriented to facilitate energy-saving and the reduction of pollutant emissions and carbon emissions. The model is first implemented to analyze the situations in 2020 and 2030 based on real planning data of China's electricity sector [3–5], which is indicated as the "business as usual" (BAU) scenario. The next scenario was implemented by removing all the inter-regional transmission connections, which is indicated as the "without transmission connections" (WTC) scenario. The results of the BAU scenario describe the expected situation of the sector based on an authoritative expansion plan for generation and transmission, and comparisons between the two scenarios reveal the low-carbon effects of inter-regional energy delivery. Finally, we assess the potential for further reductions in carbon emissions by making modifications to the planned transmission grid.

2. China's electricity transmission connections and carbon resource distributions – present and future

2.1. Regional power grid and transmission connections

The power grid of mainland China is divided into six regional power grids and one provincial power grid, which are the north, central, east, northwest, northeast, and south regional power grids and the Tibet provincial power grid (with the completion of transmission lines between Qinghai and Tibet in 2011, the Tibet provincial power grid will be incorporated into the northwest region shortly). Inter-regional connections are still limited compared to the close internal connections within the regions. Only basic, small-scale transmission capacities have been established thus far. Fig. 1 shows the regional divisions.

Fig. 2 describes inter-regional transmission connections and regional supply–demand distributions up to 2030 [4,5]. The numbers

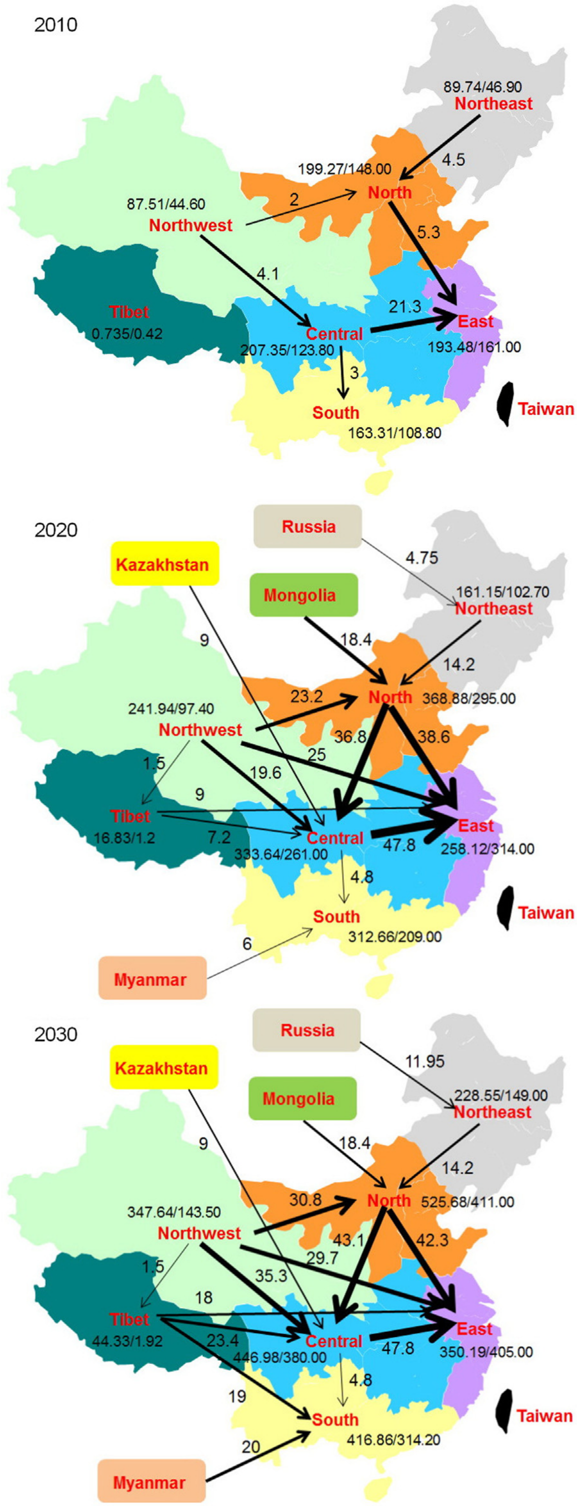

Fig. 2. Inter-regional transmission grid and power supply-demand distribution.

to the left of "/" indicate regional PGC; the numbers to the right indicate peak electric load demand; the numbers close to the links indicate transmission capacities, and the arrows reflect main transmission directions; the units are GW.

In 2010, all the regions would have the ability to balance their own power supply and demand. However, considering the need for backup capacity, maintenance, and outages in the actual operation of the power system, a certain proportion of installed

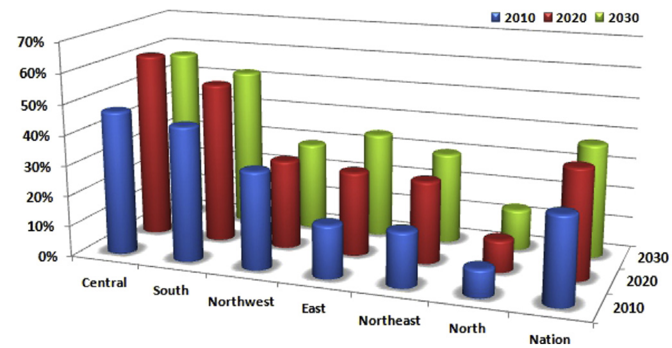

Fig. 3. Regional proportion of low-carbon power-generation capacities.

capacities should be reserved or kept on standby. Therefore, the east region had to import electricity from the central and north regions. In 2010, the inter-regional transmission capacity was only 40.2 GW, or 4.2% of the national PGC [16].

However, this situation will be changed with the development of the national economy and the bottleneck of resource utilization in the east and south regions of China. Only the northeast and northwest regions could maintain their own supply–demand balance; the central and south regions will face challenges in dry seasons when the availability of hydropower is low. The power generation ability of the north region would be significantly influenced by the wind-capacity fluctuations of over 30 GW in Inner Mongolia and the Hebei Provinces, and the supply inadequacy would be aggravated in the east region. In this case, the Chinese government and State Grid Corporation are planning to build an ambitious inter-regional transmission grid (including cross-border connections) using ultra-high-voltage transmission technology. In 2020, there will be 258 GW inter-regional transmission capacities (30 GW cross-border connections), accounting for 15% of the national PGC. The scale of inter-regional transmission capacities will be further expanded to 370 GW by 2030 (60 GW cross-border connections). This expansion in inter-regional transmission capacities will significantly change the current electricity supply and demand situation, which is primarily "regional self-balancing."

2.2. Regional distribution and structure of low-carbon power resources

Low-carbon PGC includes hydro, nuclear, wind, solar, and other renewable resources. There are significant differences in the PGC mix among the regional grids in China. In 2010, low-carbon PGC accounted for 26.8% of the national PGC mix; however, the regional distributions were extremely uneven. The central and south regions shared the highest proportions of low-carbon energy resources (45.3% and 43.1%, respectively); the proportions in the northeast and east regions were 17.5% and 15.2%. The low-carbon energy resource proportion of the north region was as low as 7.3%, whereas its proportion of conventional fossil-fuel-based PGC (including coal, gas, and oil) was as high as 92.7% (Fig. 3).

The uneven distribution of low-carbon PGC will be maintained or even exacerbated by the years 2020 and 2030. After rapid low-carbon PGC developments, the proportion of low-carbon PGC in the national PGC mix will be increased to 34.5% in 2020, 7.5% higher than that of 2010. The proportions of low-carbon PGC in the mainly of regional PGC mixes will be increased to some extent but to different degrees. The proportions in the central and south regions will be increased considerably, from 45.3% to 60.0% and 43.1% to 50.9%, respectively; the proportions of the east and northeast regions will be increased to approximately 25%; in the

northwest region, the proportion will decrease slightly, from 32.0% to 28.9%; and the proportion in the north region will increase slightly, from 7.3% to 8.3%.

The national proportion of low-carbon PGC will reach 35.5% in 2030. The proportion in the central region will decline slightly to 56.4%; in the south and northwest regions, the proportion will remain stable at the 2020 levels; the proportions of the northeast and north regions will increase slightly by approximately 3%; and the proportion of the east region will increase from 25.5% to 30.2%.

2.3. Regional coal supply for power generation

Fig. 4 presents the coal supply for power generation in China according to the regional coal supply, demand, and transportation statistics [3,10]. Transport routes in 2010 are indicated by blue solid lines and the new introduced routes toward 2030 are indicated by orange dashed lines; the blue areas on the map indicate the major coal-exporting regions, and orange areas indicate the major coal-importing regions.

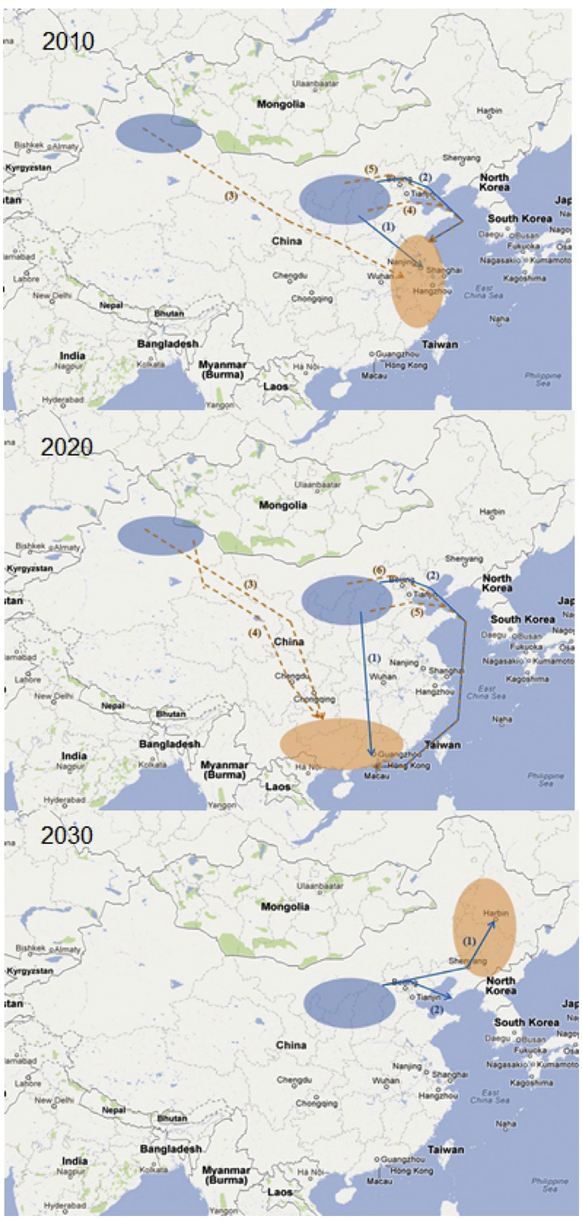

Fig. 4. Major inter-regional transport routes for coal. (For interpretation of the references to color in this figure caption, the reader is referred to the web version of this paper.)

The northwest and north regions are the major coal exporters. In the northwest region, the coal supply mainly originates from large-scale coal production bases in the province of Xinjiang, Shaanxi, Gansu, and Qinghai; in the north region, coal mainly originates from the Shanxi, Inner Mongolia, and Ningxia coal production bases. Currently, the north region is the largest exporter, whereas the northwest region will gradually expand the size of its external delivery. The major coal importers are the east, south, and northeast regions.

The current local coal production in the east region could only support approximately 1/3 of its own demand for power generation. Most of the deficiency is delivered from the north region, with 50% by rail transport (mainly by the train lines from Shanxi, Inner Mongolia, and Ningxia to Nanjing and Shanghai, marked as (1) in Fig. 4) and 50% by combined rail and shipping transport (mainly by railway from Datong to Qinhuangdao and then to Lianyungang by shipping, marked as (2)). With the increasing demand for coal to generate power in the east region, the self-supply ratio will decrease to approximately 26% in 2030 and the structure of importation will change as well. By 2030, 80% of coal importation will come from the north region and 20% will come from the northwest region. The transport mode is similar to that in 2010, with half by rail and half by combined rail and shipping transport. The major transport lines include railway from Shanxi, Inner Mongolia, and Ningxia to Nanjing and Shanghai, railway Xinjiang-Lanzhou-Xi′an- Hefei (marked as (3)); and the combined rail and shipping transport lines of Datong–Qinhuangdao–Lianyungang, Pingshuo–Huanghua–Lianyungang (marked as (4)), and Erdos–Zhangjiakou–Caofeidian–Lianyungang (marked as (5)).

The self-supply ratio of the south region is approximately 60% at present. The remaining 40% mainly originates from the north region, with 50% by rail transport (mainly by the train lines from Shanxi, Inner Mongolia, and Ningxia to Guangzhou, marked as (1)) and 50% by combined rail and shipping transport (mainly by railway from Datong to Qinhuangdao and then to Guangzhou and Shenzhen by shipping, marked as (2)). Owing to the limited local expansion capacity of coal, this ratio will decrease dramatically to as low as 30% in 2030. By then, 2/3 of the imports would originate from the north region, with the remaining 1/3 originating from the northwest region. Furthermore, 75% of the imports would be delivered by rail, and the remaining 25% would be delivered by combined rail and shipping. The major transport routes include railway from Shanxi, Inner Mongolia, and Ningxia to Guangzhou and Shenzhen, Wurumqi–Lanzhou–Chongqing-Guiyang (marked as (3)), Hami–Dunhuang–Xining–Chengdu–Guiyang (marked as (4)); and the combined rail and shipping transport lines of Datong–Qinhuangdao–Guangzhou, Pingshuo–Huanghua- Guangzhou (marked as (5)), and Erdos–Zhangjiakou–Caofeidian–Guangzhou (marked as (6)).

The self-supply ratio of the northeast region is relatively large at 76%. Imports mainly originate from the north region, with 2/3 delivered by railway (mostly by the train line from Shanxi, Inner Mongolia, and Ningxia to Shenyang and Changchun, marked as (1)), and 1/3 by combined rail and shipping transport (mainly by railway from Datong to Qinhuangdao and then to Shenyang and Changchun by shipping, marked as (2)). This self-supply ratio will be decreased to 44% in 2030, whereas the importation source and transport routes will be similar to those in 2010.

3. Model, method and data

A fine-grained electricity dispatch model is proposed to simulate and optimize the operation of power systems. As this paper

aims to assess the maximum potential of CO_2 mitigation, the objective of the model is to minimize the overall carbon emissions of the electricity sector, including carbon emissions from not only fossil fuel combustion but also fuel exploitation and transport. Moreover, the model considers regional differences in the power-generation mix and integrates inter-regional electricity delivery with limited transmission capacity constraints.

This model reflects an important policy on electricity dispatch in China that is oriented toward facilitating reductions in energy consumption, pollution, and carbon emissions by setting a model objective. In 2007, the Chinese government decided to pilot-test energy-saving generation dispatching (ESGD). Rules on ESGD policy were jointly issued by the National Development and Reform Commission (NDRC), the State Electricity Regulatory Commission of China (SERC), and the Ministry of Environmental Protection (MEP) [36]. The rules aimed to reform the existing equal-share generation dispatching mode, thereby reducing fossil energy consumption, pollution emissions, and carbon emissions. ESGD prioritizes low-carbon power sources (e.g., renewable resources, clean energy) and highly efficient coal-fired generation units. Five provinces have been selected to pilot-test the new ESGD rules since 2007. Summary reports indicated that coal consumption for thermal power generation was reduced largely owing to the new ESGD rules in 2009 [37,38]. This policy was further expanded in the south regional power grid and is expected to expand its implementation scope in the following years. Therefore, the proposed electricity dispatch model could effectively simulate the operation situations of China's electricity sector (under ESGD) in the future.

This model dispatches power generation for the various regional power sources based on given PGC expansion plans. Each regional power grid is set as a decision-making object with a specific type of power source (e.g., hydro, wind, nuclear) as a basic decision-making unit. The basic time unit is set as one "year." The model integrates formulations of the technical characteristics of a power system to better simulate the operation of a real power system, including the energy supply–demand balance, peak power capacity demand, reasonable capacity reserves, availability of power sources, maximum utilization of renewable energy, transmission capacity limit, and transmission losses.

3.1. Objective function of the model

The objective is to minimize national overall carbon emission, which is

$$\min \sum_{i=1}^{N}\sum_{j=1}^{M} g_{i,j}\cdot e_{i,j} \tag{1}$$

where $g_{i,j}$ is the decision variable denoting power generation of source j in region i and $e_{i,j}$ is the corresponding GCEI. GCEIs for the same type of power source in different regions are always different owing to differences in generating technologies, fuel type, and installation year. N is the number of regions, and M is the number of power source types.

For fossil-fuel-based PGC, their GCEI incorporates carbon emission from fuel exploitation, transport, and combustion for generation as follows:

$$e_{i,C} = e_{i,C}^{g}\cdot(1+s_i^I+s_i^O\cdot\lambda_i^O)\cdot(1+s_i^E) \tag{2}$$

where $e_{i,c}$ is the GCEI for power source C in region i and $e_{i,C}^{g}$ is the portion of the carbon emissions incurred by fuel combustion. We reasonably assume that the fuel imported outside the region should be transported major rail or shipping routes, denoted as s_i^O, and then delivered by transport network within the region, denoted as s_i^I. Therefore, for the imported fuel, the overall GCEI would be higher than the local-supply fuel, which is mainly influenced by s_i^O. s_i^I and s_i^O are region-wide average parameters. λ_i^O is the proportion of fuel imported from outside the region. s_i^E is the portion of the carbon emissions incurred by fuel exploitation.

3.2. Constraints of the model

3.2.1. Power supply–demand balance

The regional power supply–demand balance should be guaranteed. For any region i, $i=1, 2\ldots\ldots N$, we have

$$\sum_{j=1}^{M} g_{i,j}\cdot(1-r_i^G)+\sum_{h=1}^{N} t_{i,h}^I-\sum_{h=1}^{N} t_{i,h}^O = D_i\cdot(1+r_i^D) \tag{3}$$

where D_i is the total terminal electricity demand in year i. $t_{h,i}^I$ is the decision variable that indicates net power generation imported to region i from region h. $t_{i,h}^O$ is the decision variable that indicates power generation exported from region i to region h. The two decision variables should be set to zero if there are no transmission connections between the two regions. r_i^G is the region-wide average ratio of auxiliary electricity energy, and r_i^D is the region-wide average loss rate to deliver electricity from power plants to terminal users in region i, including the transmission losses and distribution losses of all voltage levels.

Inter-regional transmission losses are closely related to the transmission technology (AC or DC), voltage level, and length of the transmission lines. In the years 2020 and 2030, the presence of multi-transmission-channels between regions will complicate the analysis of this study. The different transmission channels adopt different transmission technologies, voltage levels, lengths, and starting/ending points. For simplicity, we combine the related channels to obtain an average transmission loss.

The model considers transmission losses to deliver electricity between regions; thus, we have

$$t_{i,h}^I = t_{h,i}^O\cdot(1-r_{h,i}^T) \tag{4}$$

where $r_{h,i}^T$ is the average transmission loss rate between regions i and h.

3.2.2. Power availability

There are significant differences in the availability of various power sources. Without the deployment of large-scale storage capacity, the availability of wind and solar power would be largely restricted by the characteristics of the local climate resources. The availability of hydro power is subject to seasonal variations in the runoff and the capacity of reservoirs. The availability of fossil-fuel-based power plants is mainly affected by the abundance of the primary fuel supply. In addition, the equipment for any type of power source always requires maintenance, which might require days or weeks to complete. Moreover, for power systems, a certain additional amount of capacity should be always available as spinning or cold reserves to guarantee the security of the power system operation against various fluctuations, outages, and security risks. Therefore, the actual availability would be lower than theoretical values. For example, the availability of fossil-fuel-based power sources is approximately 0.7–0.8, and the availability of hydro power differs considerably in different regions (0.3–0.7). The availability of wind is approximately 0.2–0.4, with off-shore sites having higher availabilities than on-shore sites [39].

The constraint on the availability of power generation can be expressed as

$$0\le g_{i,j}\le v_{i,j}\cdot C_{i,j}\cdot H \tag{5}$$

where $C_{i,j}$ is the installed capacity for power source j in region i, $v_{i,j}$ is the availability rate, and H is the number of hours within the basic decision period. The value of H for 1 year is 8760.

3.2.3. Penetration of intermittent power generation

Intermittent power sources, such as wind and solar, will be dispatched for generation with a higher priority owing to their low GCEI in this model. However, penetration (the proportion of the generation mix) of intermittent power generation (IPG) will increase rapidly in the coming years as a result of technology improvements. In this case, the availability of the intermittent sources would be related to their penetrations because when the penetration of IPG exceeds a critical level, the controllable capacity would be unable to handle the incurred fluctuations. In this case, the availability of the intermittent power sources would be lowered by the abandonment of IPG on some occasions.

The situations described above could be reflected by integrating a constraint that correlates the availabilities of intermittent sources to their penetration in each region when the penetration exceeds a critical level. The excess part of the IPG would be abandoned by a certain proportion. It is reasonable to suppose that the correlation is a linear function, meaning that the proportion will remain unchanged when the penetration does not vary in a large range [39]. The constraint is formulated as

$$g_{i,j}^M \le C_{i,j}\cdot v_{i,j}\cdot H - C_{i,j}\cdot v_{i,j}\cdot H\cdot\left(\sum_{j=1}^{M_M} g_{i,j}^M / \sum_{j=1}^{M} g_{i,j} - r_i^M\right)\cdot p_i^M$$

$$\sum_{j=1}^{M_M} g_{i,j}^M \ge r_i^M\cdot\sum_{j=1}^{M} g_{i,j} \qquad (6)$$

where $g_{i,j}^M$ is the IPG of source j in region i, M_M is the number of intermittent sources, r_i^M is the critical level of penetration, and p_i^M is the ratio of IPG abandonment. This constraint is put into effect only when the penetration of IPG exceeds the critical level, as indicated by the right part of (5).

In this paper, the critical level of IPG is set to 10%, and the ratio of IPG abandonment is set to 20% [39].

3.2.4. Limits of transmission availability

The availability of inter-regional transmission connections are considered in the model as follows:

$$\begin{cases} 0 \le t_{i,j}^I \le T_{i,j}\cdot v_{i,j}^T\cdot H \\ 0 \le t_{i,j}^O \le T_{i,j}\cdot v_{i,j}^T\cdot H \end{cases} \qquad (7)$$

where $T_{i,j}$ i the transmission capacity between regions i and j and $v_{i,j}^T$is the corresponding availability.

For inter-regional electricity transmission, the continuity and stability of the electricity supply for an exporting region would be affected by the region's generation mix. More specifically, if an exporting region includes large proportions of hydro and wind power, its supply ability would fluctuate considerably in different seasons. However, the seasonal fluctuations could not be explicitly expressed as the decision time unit is set as one “year.” Instead, we set more strict restrictions on the availability of transmission capacities. Moreover, importing regions would prefer the transmitted electricity to follow a profile similar to its day electricity demand curve (differentiated by approximately 20–40% in the peak and off-peak demand periods) instead of a flat line. This will certainly result in reductions in the availability of transmission lines. Moreover, equipment maintenance and unexpected outages should be considered as well.

Considering the above factors, transmission availability should be much lower than the theoretical values, which are approximately 0.6–0.7. In this paper, the YGH cap for various transmission connections is uniformly set to 5500.

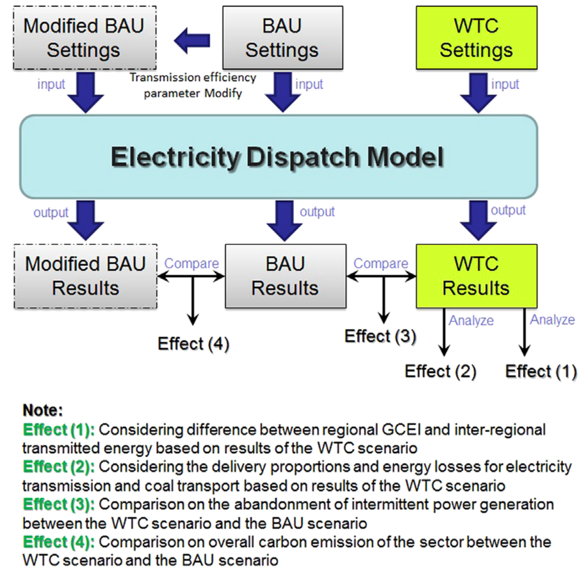

Fig. 5. Procedures and specifications of the assessment method.

3.3. Low-carbon effect assessment method

The low-carbon effects incurred by inter-regional electricity transmission can be attributed to four aspects:

1. First, electricity can be more fully transmitted from low- to high-GCEI regions to reduce overall carbon emissions;
2. Second, the overall delivery efficiency may be enhanced by coordinating energy delivery in the form of coal transport and electricity transmission;
3. Third, abandonment of IPG will be reduced because the penetration of IPG would be reduced in the exporting regions, thereby making better use of low-carbon energy resources;
4. Fourth, improvements in technology efficiency will reduce electricity delivery losses.

The first aspect is abbreviated as “transmission between regions,” δ_T. δ_T is expressed as

$$\delta_T = \sum_{i=1}^{N}\sum_{j=1}^{N} t_{i,j}^O\cdot(e_i^R - e_j^R) \qquad (8)$$

where e_i^R and e_j^R are the regional GCEIs of regions i and j, respectively.

The second aspect is abbreviated as “coal-elec. coordination,” δ_C. δ_C is expressed as

$$\delta_C = \frac{p_E}{p_C}\cdot D^C\cdot l_{i,j}^C\cdot e^R - \sum_{i=1}^{N}\sum_{j=1}^{N} t_{i,j}^O\cdot e_i^R\cdot l_{i,j}^E \qquad (9)$$

where p_E and p_C are the proportions of energy delivery in the form of electricity transmission and coal transport, respectively. D^C is the total amount of energy delivered by coal transport. $l_{i,j}^C$ and $l_{i,j}^E$ are the rate of delivery loss for coal transport and electricity transmission from region i to j, respectively. e^R denotes the national GCEI. More specifically, the right item in (7) is real carbon emission incurred by electricity transmission, whereas the left item is carbon emission incurred by the transmitted energy if the same amount of energy is delivered by coal transport. The difference between the two items is the low-carbon effect of switching delivery patterns.

The third aspect is abbreviated as “abandon of intermittent generation,” δ_I. First, the abandonment of IPG for different regions

Table 1
Regional electricity demands [7–9].

Electricity demand (TWh)	Nationwide	North	Central	East	Northeast	Northwest	South	Tibet
2010	4199.8	1005.8	773.2	1037.4	342.4	333.7	705.2	2.0
2020	7799.0	1920.0	1420.0	1850.0	619.0	605.0	1380.0	5.0
2030	10,566.0	2590.0	2030.0	2320.0	891.0	875.0	1851.0	9.0

Table 2
Regional power generation capacities [8,9].

Power sources (GW)		Nation-wide	North	Central	East	Northeast	Northwest	South
Total	2010	960.36	202.77	214.44	198.26	90.06	87.49	166.61
	2020	1727.69	376.52	328.12	259.03	168.21	243.14	335.84
	2030	2421.41	533.32	456.17	366.80	236.41	348.84	435.54
Hydro	2010	204.11	2.56	87.47	18.72	6.90	23.32	64.70
	2020	388.68	2.56	185.77	18.72	6.90	38.89	119.41
	2030	471.39	2.56	206.47	18.72	6.90	44.19	148.92
Coal	2010	663.03	182.64	111.29	149.22	74.03	58.97	86.71
	2020	1112.10	336.10	130.13	177.42	123.05	170.91	142.67
	2030	1475.03	460.60	190.13	224.44	165.75	246.21	187.73
Gas	2010	25.71	2.02	2.09	14.81	0	0.53	6.25
	2020	32.11	2.02	3.43	14.81	0	1.04	10.80
	2030	47.24	2.02	4.78	19.86	0	1.04	19.53
Nuclear	2010	15.64	0	4.95	5.74	0	0	4.95
	2020	84.45	4.00	10.00	31.57	9.00	0	29.88
	2030	164.65	16.70	34.00	55.57	13.50	0	44.88
Wind Power	2010	32.55	12.03	1.54	4.87	8.81	4.62	0.68
	2020	101.61	22.30	2.51	13.80	25.00	30.00	8.00
	2030	182.00	40.00	8.00	28.00	40.00	54.00	12.00
Others	2010	0.27	0.02	0.01	0.12	0	0.07	0.02
	2020	10.00	1.90	1.80	1.80	1.20	1.10	1.90
	2030	20.00	3.80	3.60	3.60	2.40	2.20	3.80

Table 3
GCEI for fossil fuel based power sources [7–9].

GCEI (g/kWh)		Nationwide	North	Central	East	Northeast	Northwest	South
Coal	2010	879.82	850.74	965.65	815.16	943.44	899.63	918.87
	2020	723.56	695.11	789.01	666.05	770.86	735.06	750.78
	2030	591.78	567.95	644.68	544.21	629.85	600.60	613.44
Gas	2010	514.33	510.44	579.39	489.10	566.07	539.78	551.32
	2020	424.31	417.07	473.40	399.63	462.52	441.04	450.47
	2030	345.67	340.78	386.81	326.53	377.91	360.36	368.07

in the BAU scenario can be calculated by implementing the electricity dispatch model, denoted as $g_{I,i}^{BAU}$; then, the same results of the WTC scenario, denoted as $g_{I,i}^{WTC}$, could be obtained as well. δ_I is expressed as

$$\delta_I = \sum_{i=1}^{N} (g_{I,i}^{WTC} - g_{I,i}^{BAU}) \cdot e_i^R \tag{10}$$

The fourth aspect is abbreviated as "tech improve for transmission," denoted as δ_M. First, we implement the electricity dispatch model for the BAU scenario to obtain the overall carbon emissions of the sector; improvements in electricity transmission efficiency have been incorporated toward 2020 and 2030 in the BAU scenario. Then, we use the current parameters of the electricity transmission efficiency to replace the 2020 and 2030 data for the BAU scenario, and the model is implemented again to obtain another result for the overall carbon emissions. This result depicts the situation with no technology improvements. Differences between the two scenarios indicate the effects of δ_M.

Table 4
Rates of auxiliary electricity energy [7–9].

	Hydro (%)	Fired-based (%)	Nuclear (%)	Renewables (%)
2010	0.36	6.5	3.5	2.0
2020	0.29	5.3	2.9	1.6
2030	0.24	4.3	2.3	1.3

The procedures and specifications of the assessment method are presented in Fig. 5.

Moreover, we divide the low-carbon effects from the generation side into two major aspects, denoted as "tech improve for generation" and "expansion of low-carbon capacity." For the effects of "tech improve for generation," the assessment method is the same as that for "tech improve for transmission"; in this case, we replace the generation efficiency parameters but not the transmission efficiency parameters. For the effects of "expansion of

Table 5
Rates of Intra-region electricity delivery losses [7–9].

	2010	2020	2030
Intra-region delivery losses	6.50%	5.31%	4.34%

Table 6
Average cross-region transmission losses [7–9].

Transmission connections	2010 (%)	2020 (%)	2030 (%)
Northeast-North	3.68	3.02	2.48
North-East	3.73	2.53	2.07
North-Central	5.19	4.26	3.50
Central-East	4.06	3.18	2.61
Central-South	4.94	4.05	3.33
Northwest-North	4.36	3.58	2.94
Northwest-East	6.22	4.82	3.98
Northwest-Central	2.65	2.17	1.78
Northwest-Tibet	7.45	6.11	5.01
Tibet-East	12.75	10.46	8.58
Tibet-Central	7.53	6.18	5.07
Tibet-South	11.39	9.34	7.67

Table 7
Carbon emission incurred by different kinds of transports [7–9].

Carbon emission (kg/Mt· km)	Railway	Shipping	Highway
2010	8273	16,790	140,903
2020	6758	13,716	115,106
2030	5524	11,211	94,080

low-carbon capacity," we implement the electricity dispatch model for a modified BAU model that applies the current generation capacity mix (proportions of various power sources) to 2020 and 2030 (without changing the overall scale of the PGC) to obtain another result for overall carbon emissions. This result depicts the scenario in which all types of power sources, regardless of their GCEI, would be expanded at the same pace. The effects of "expansion of low-carbon capacity" could be calculated by comparing this result with that of the BAU scenario.

3.4. Basic data for the scenario settings

Basic data were collected from the following resources for the scenario settings:

1. Historical data for 2010 were obtained from "China Statistics Yearbook 2010" [1] published by the National Bureau of Statistics of China;
2. Planning data on power-generation and transmission capacities were obtained mainly from the "Overall Design Report for Power Transmission Grid Planning for State Grid of China and China Southern Grid" [4,5];
3. Data on future energy delivery, particularly coal transport until 2030, were mainly obtained from the "2050 China Energy and CO_2 Emissions Report" [3] and the "China Sustainable Development Strategy Report 2009 – China's Approach toward a Low Carbon Future" [10] published by the China Academy of Science;
4. For data related to the development of technologies, such as the generation, transmission, and distribution efficiencies and the auxiliary rates, the data were partly obtained from available references [6–8,10,28] and partly estimated by extrapolating the trends of historical data considering advancements in technology;
5. For data that could not be directly obtained from available sources, such as the availability of generation sources and transmission connections, the data were reasonably assumed from experience in practical engineering. In this study, we sought to analyze regional differences for all types of data; however, for certain specific data, such as the rate of auxiliary electricity energy and the rate of intra-regional electricity delivery losses, regional differences were ignored because it was difficult to find the corresponding data. More importantly, regional differences in the data are not expected to impact the final results.

Table 8
Overall carbon emission intensity for coal based power generations [7–9].

Intensity (g/kWh)	2010	2020	2030
North	926.03	756.63	618.22
Central	1053.70	860.95	703.46
East	918.22	769.02	643.59
Northeast	1038.18	854.89	698.18
Northwest	973.27	779.15	623.74
South	1033.58	858.51	705.11

The regional electricity demands are listed in Table 1.

This case is established based on the power capacity expansion plan analyzed in Section 2. The regional installed power capacities are listed in Table 2.

The GCEIs of hydro, nuclear, wind, solar, and other renewable resources are set as zero for simplicity; the capacity of oil-fired-based power plants is very small, and thus, their emissions are also ignored. GCEI for fossil fuel-based power sources are listed in Table 3. The data in Table 3 reflect only the portion of the intensity from fossil fuel combustion.

The rates of auxiliary electricity energy and intra-regional delivery losses are listed in Tables 4 and 5, respectively. Regional differences are ignored owing to the lack of available data. Table 6 lists the average inter-regional transmission losses.

Table 7 shows the carbon emission incurred by different types of transport. Table 8 shows the overall carbon emission intensity for coal-based power generation, integrating emissions incurred by fossil fuel exploitation, transport and combustion.

The availability of various power-generation sources could be reflected by the concept of the "yearly generating hour" (YGH), which represents the utilization of power sources in the yearly average sense, equivalent to annual cumulative generation divided by the capacities [8,28]. Regional differences are considered based on the distribution of the natural resources. For hydro power, the cap of YGH is set as 3600 in the south, east, central and northeast regions considering their abundant hydro resources, whereas YGH is set to 3200 in the northwest and north regions. For wind power, the differences between on-shore and off-shore types are considered. As wind power in the northeast, northwest, north and central regions are mainly on-shore, the YGH caps are set as 2000, 2200 and 2400 in the year of 2010, 2020 and 2030, respectively; wind power in the south and east regions is mainly off-shore and the YGH caps are 10% higher. For nuclear and fossil fuel power-generation sources, regional differences are ignored. The YGH cap for nuclear is uniformly set as 7800; The YGH cap for coal is set as 7000 considering the need for maintenance and reserves; The YGH cap for gas is set as 3000 because the gas-based power plants always play the role of peak-load shaving in China.

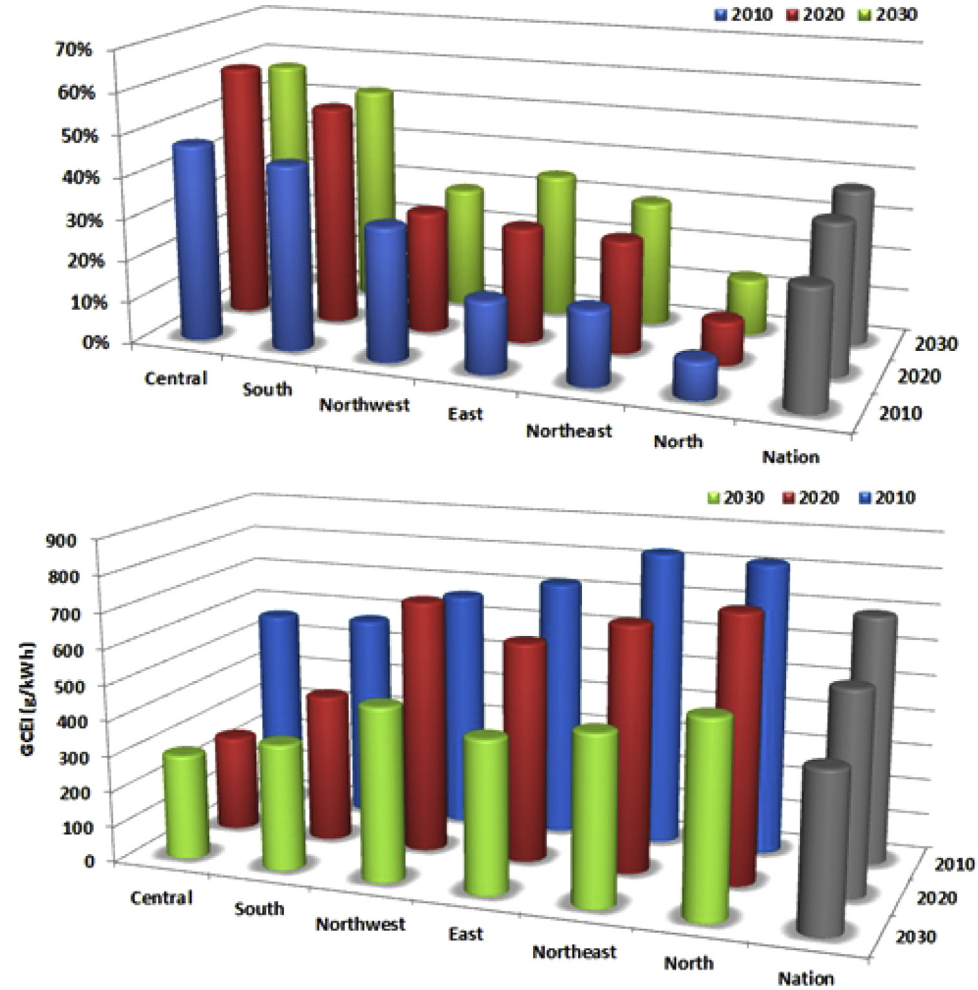

Fig. 6. Low-carbon power-generation proportions and GCEI based on simulation of scenario BAU.

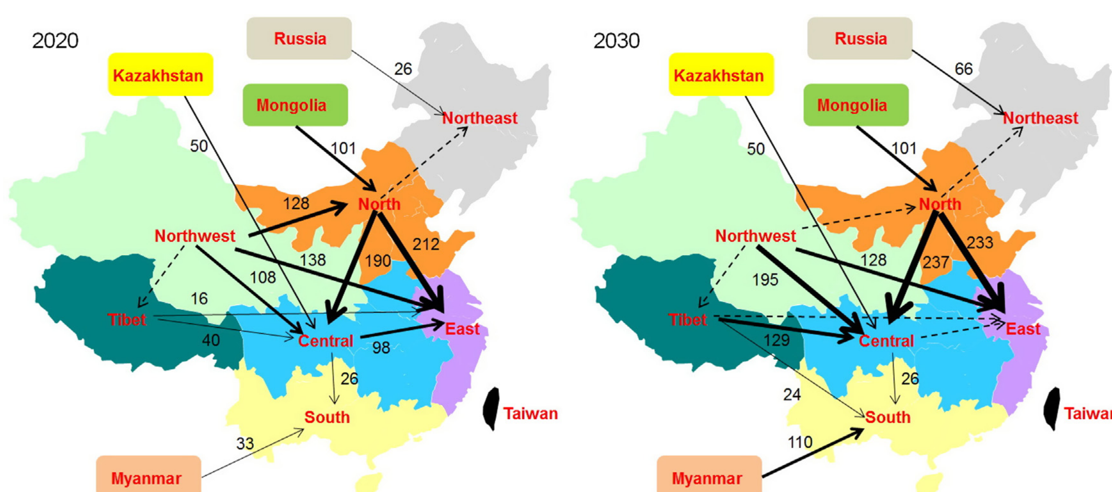

Fig. 7. Inter-regional electricity transmission in 2020 and 2030. (For interpretation of the references to color in this figure caption, the reader is referred to the web version of this paper.)

4. Empirical analysis

4.1. Analysis of scenario BAU

In the BAU scenario, the total carbon emission of the sector will be 4.74 Gt in 2020 and 4.81 Gt in 2030, representing approximately 40% more than that measured in 2010. The results indicate that the total carbon emission will still maintain a relatively high rate of increase before 2020 and will subsequently remain stable from 2020 to 2030. From 2010 to 2020, the average annual rate of increase will slow to 3.5% compared to more than 8% from 1990 to 2010. Approximately 90% of the total carbon emissions are derived from fuel combustion and 10% are derived from fuel transport and exploitation.

As shown in Fig. 6, the national proportion of low-carbon power generation will increase to 27.6% in 2020 and 31.2% in 2030, compared to 22.9% in 2010. Meanwhile, the national GCEI is reduced to 567.3 g/kWh in 2020 and 435.9 g/kWh in 2030, 25.1% and 42.5% lower than that of 2010, respectively. However, the unbalanced regional distribution of GCEI will be aggravated, creating great potential for carbon emission mitigation by inter-regional electricity transmission. In 2030, the central and the north regions have the lowest and highest GCEI. Specifically, 538.9 g/kWh and 295.6 g/kWh, a difference of more than 50% compared to the national GCEI.

Fig. 7 shows the results of inter-regional electricity transmission in 2020 and 2030 for the BAU scenario. The situations in 2020 and 2030 are depicted. The solid lines with colors indicate that the lines essentially transmit electricity, whereas the dashed lines indicate that no electricity is transmitted; numbers close to the lines indicate the amount of transmitted electricity and the arrows reflect transmission directions; the units are TWh.

The total transmitted electricity is increased to 1125.1 TWh and 1230.8 TWh, accounting for 14.6% and 12.0% of the national electricity demand compared to 5.8% in 2010. The north and northwest regions are major exporters, delivering approximately 650 TWh and 800 TWh of electricity in 2020 and 2030 to the east and central regions. Hydro power bases established in southern Tibet are also important exporters, transmitting approximately 55 TWh and 150 TWh of low-carbon hydro power outward. For the south region, the imported electricity mainly comes from the large-scale power stations in southern Tibet and Myanmar. It should be noted that because the analyzed time scale is set to one “year,” seasonal inter-regional electricity delivery within 1 year could not be reflected in this case.

For the BAU scenario in 2020, the scale of inter-regional energy delivery, including coal transport for power generation and electricity transmission, would be increased to 33% of the total energy consumption for the sector and slightly reduced thereafter to 32% in 2030 compared to 24% in 2010. By comparison, the energy delivered by transmission grid would increase much faster. Its proportion in the mix of energy delivery would be increased from 23.1% in 2010 to 44.3% in 2020 and later slightly reduced to 37.7% in 2030. In 2020, the total carbon emission incurred by energy delivery is 0.29 Gt of CO_2, of which 82.9% is incurred by coal transport and 17.1% by electricity transmission. By switching from coal transport to electricity transmission, 0.11 Gt of CO_2 is abated, which improves the overall energy delivery efficiency by approximately 25%. Similar results could also be observed in 2030.

4.2. Assessment of scenario WTC and comparison

Next, the model is implemented in the WTC scenario, which is modified by removing the inter-regional transmission connections based on the data from the BAU scenario. It should be noted that without the connections, the east region would not be able to maintain a self-supply–demand balance, owing to inadequate local PGC. In this case, a reasonable solution is to add “virtual” PGC in the inadequate region. Carbon emissions produced by the “virtual” PGC should be considered in the results. Considering the energy resource characteristics of the east region [1,3], we reasonably assumed that the “virtual” PGCs are all coal-based power plants, as there would be no significant headroom to expand with additional low-carbon PGC.

Regardless of the inter-regional transmission connections, overall carbon emission for the WTC scenario would be increased to 5.06 Gt in 2020 and 5.30 Gt in 2030. The results indicate significant mitigation effects of 0.32 Gt in 2020 and 0.49 Gt in 2030, thereby accounting for 6.8% and 10.2% of national carbon emission of the sector. Mitigation in 2020 is approximately the size of France's annual CO_2 emissions in 2010, the world's eighteenth largest emitter [11], and mitigation in 2030 is more than the amount of the United Kingdom's annual CO_2 emissions in 2010, the world's 10th largest emitter [11]. However, the effects might be neglected if we only consider the generation side, which is standard for available studies, leading to a significant underestimation of 25.6% and 15.1% of mitigation effects for the low-carbon budget of the electricity sector.

The lack of inter-regional transmission connections would lead to slightly restricted utilization of low-carbon power resources, represented as the abandonment of IPG. Intermittent power sources include, for instance, wind and solar. In power system operations, the availability of intermittent power sources is related to their penetration (the proportion of the generation mix for each regional power grid) because the controllable PGC (mainly fire-based and hydro power plants) would be unable to handle the intermittent fluctuations when the penetration exceeds a critical level [39]. In this case, part of the IPG should be abandoned by a certain proportion. In the 2030 WTC scenario, the penetration of IPG in the northwest and northeast regions is 17.1% and 12.8%, respectively, exceeding the 10% critical level. Twenty percent of the excess IPG would be abandoned and replaced with coal-based power generation [39]. However, in the BAU scenario, IPG abandonment could be reduced by 74%, owing to the support of the inter-regional transmission grid, whereby the penetration of IPG is diluted by the outwardly transmitted electricity. As a result, the abandonment of IPG would produce an additional 8.98 Mt of carbon emissions in 2030. These effects would become increasingly significant with the increase in IPG penetration. Because the analyzing timescale is one “year,” this study does not discuss the abandonment of IPG in short timescale power system operation, which might be incurred by frequency control, voltage control, or peak-valley load regulation [40]. We approximate these factors by reducing the availability of wind power generation.

Furthermore, we attempt to identify the contribution of carbon emission mitigation incurred by inter-regional electricity transmission from the perspective of the entire sector. If no generation or transmission action is taken to mitigate carbon emission, we could reasonably assume that the current GCEI would be maintained through 2020 and even 2030. In this case, the overall carbon emission of the sector would increase drastically to 6.31 Gt in 2020 and 8.55 Gt in 2030. Considering the results of the BAU scenario, carbon emission reductions of 1.25 and 3.25 Gt are obtained for the entire sector in 2020 and 2030, respectively. Hence, mitigation incurred from the transmission side would contribute to as much as 25.6% and 15.1% of the low-carbon budget of the sector in 2020 and 2030, respectively. The structure of this budget is described in Fig. 8.

5. Recommendations and conclusion

5.1. Recommendations on further reducing carbon emissions

According to the results of the BAU scenario, the utilization of inter-regional transmission connections differs considerably. A portion of connections will reach their limits, whereas others will remain unused. This situation indicates that there is still potential for improvement if we modify the planned transmission grid. To this end, we implement the dispatch model again, relaxing the constraints on the cap for inter-regional transmission capacities. The results indicate that in 2020, we can reduce carbon emissions by an additional 0.16 Gt, increasing the low-carbon effects of the BAU scenario by 50%. Meanwhile, approximately the same scale of transmission capacities could be retained if we build inter-regional transmission lines to support electricity delivery exactly without any additional capacity and significant modifications are observed. The modifications could be sorted into several strategies. The first strategy is to enlarge the outward transmission capacity from the

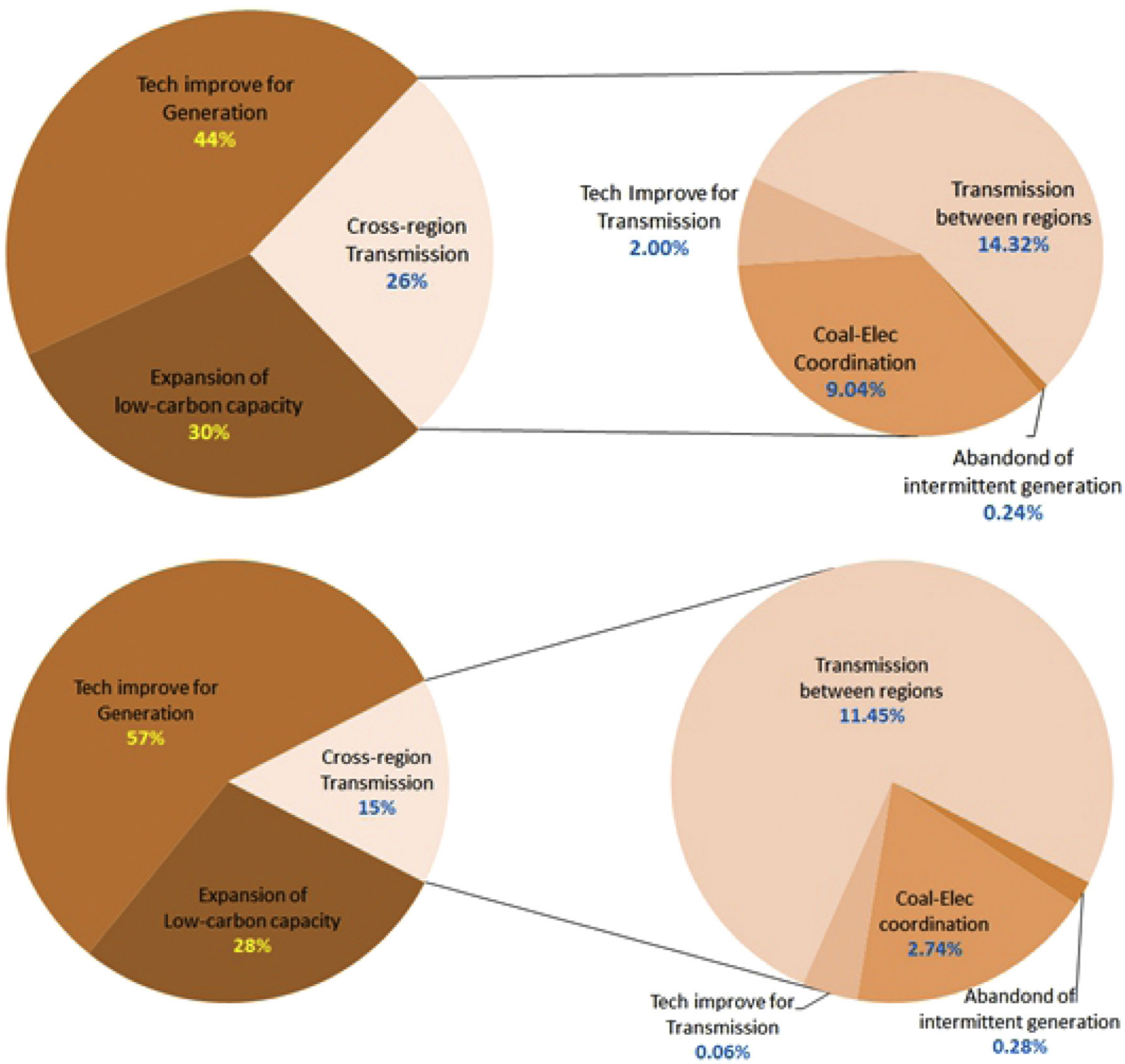

Fig. 8. Structure of the low-carbon budget for the sector.

northwest region from 70 to 128 GW and concentrate the connections to the central region while canceling connections to the north and east regions. The second strategy is to cancel connections from southern Tibet to the central and east regions while adding a 10-GW connection to the south region. The third strategy is to increase the capacity from the central region to the south region from the current 4.8 GW to 24.2 GW to support additional low-carbon power generation from the central and northwest regions in place of coal-based power generation in the south region. The fourth strategy is to expand the connection from the north region to the east region by 60% instead of using the connections from the central region to the east region. However, in 2030, only slightly improved low-carbon effects could be observed (less than 0.05 Gt, or 1% of the total sector emissions). The main reason for this slight improvement is that the current planned inter-regional transmission grid for 2030 in the BAU scenario is already sufficient to support various patterns of electricity transmission. However, we could reduce the transmission capacities by 30% compared to the current expansion plan at the expense of a 1% increase in emissions.

5.2. Conclusion

In conclusion, our analysis highlights the significant potential reductions in carbon emissions from China's planned inter-regional transmission grid. CO_2 emissions could be reduced by 0.32 and 0.49 Gt by 2020 and 2030, respectively, accounting for 6.8% and 10.2% of the national carbon emissions in the sector. These effects were ignored in previous analyses, which thus did not consider up to 25.6% and 15.1% of the low-carbon budget of China's electricity sector in 2020 and 2030, respectively, leading to significant underestimations. The mitigation effects are mainly composed of four aspects. Transmission between regions with different GCEIs provides the majority of the reductions in CO_2 emissions. Further analysis reveals that the reductions can be increased by an additional 50% by modifying the transmission grid to minimize overall carbon emissions in 2020; this additional reduction in emissions allows the transmission capacity to be reduced by 30%, thus increasing the efficiency of the plan. These results may be useful for the government and electricity grid companies in developing reasonable policies in the future. As the proposed dispatch model is formulated with good versatility, the model can be further expanded to consider inter-province or even intercity energy delivery and dispatching power generation among individual power plants when the corresponding fine-grained data are available. We believe that this model could also be used in other countries.

This analysis attempts to provide reasonable estimates for the sector's low-carbon budget from the perspective of the entire electricity sector. However, one limitation of this paper is a lack of studies on the effects from the demand side due to the lack of reliable

data at the national level. Moreover, discussions on emerging technologies, such as carbon capture and storage, battery storage, and electric vehicles, are beyond the scope of this study given their large uncertainties in terms of technological progress and commercial utilization. We will consider these issues in future research.

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